

# Super Beams

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High intensity conventional horn-focused neutrino beam produced by MW-class proton accelerator, “super beam”, provides opportunity to further develop neutrino physics, especially long baseline (LBL) oscillation experiments. Several super beam LBL experiments are proposed as next generation high sensitivity, high precision experiments before neutrino-factory era. Sensitivities of the experiments are one orders of magnitude or more higher than the current ones. The experiments and their physics potential are introduced.

## 1. Introduction

“Super beam” means high intensity neutrino beam obtained from decays of horn-focused secondary pions which are produced using a (Multi-)MWatt proton beam. The beam produces pure  $\nu_\mu$  beam with  $\nu_e$  contamination of the order of 1% from muon and Kaon decays. The sign of neutrino,  $\nu_\mu/\bar{\nu}_\mu$ , can be switched by flipping the polarity of the horn focusing system. It is strongly motivated by future high precision high sensitivity long baseline (LBL) neutrino oscillation measurements. Therefore, in this presentation, I focus on LBL neutrino oscillation experiments with super beam while there are other interests on super beam such as study of neutrino interactions, spin structure of nucleons and so on.

The LBL neutrino oscillation experiments could be classified into 3 generations [1].

### 1st generation experiments (Present):

Most important goal of the experiments is the confirmation of the neutrino oscillation found in the atmospheric neutrino [2]. K2K [3], MINOS [4] and ICARUS [5]/OPERA [6] belong to this generation.

### 2nd generation experiments (~10 years):

The experiments are designed and optimized after the evidence of neutrino oscillation and their most important goal is discovery of  $\nu_\mu \rightarrow \nu_e$  appearance. The ex-

periments typically use a MW proton beam and ~50 kt detector and include T2K 1st phase (T2K-I) [7], NO $\nu$ A [8] and C2GT [9].

### 3rd generation experiments (10~20 years?):

Main purpose of the experiments will be search for CP violation in lepton sector and/or determination of mass hierarchy through  $\nu_e$  appearance measurements. The discovery of  $\nu_e$  appearance is a prerequisite to go this phase. Projects in this generation typically assume a multi-MW proton beam and a Mton detector.

Usually “super beam” experiments in a wide sense cover 2nd and 3rd generation experiments. The 2nd generations experiments T2K-I and NO $\nu$ A are described in detail in other talks [10,11]. Therefore, the 3rd generation projects are mainly described in this presentation.

#### 1.1. $\nu_e$ appearance probability

Mass hierarchy and CP violation can be probed by measuring  $\nu_e$  appearance. In Fig. 1, relevant oscillation probabilities are plotted. As shown in the figure, the CP asymmetry can be as large as 40% even at  $\delta = \pi/4$ . Matter effect also produces the difference between  $\nu$  and  $\bar{\nu}$  and mimics the CP violation effect. The size the matter effect increases linearly with neutrino energy. Therefore, in order to be sensitive only on pure CP violation, the lower energy is better. In Fig. 1, the size of the matter effect is also drawn. At 1st os-

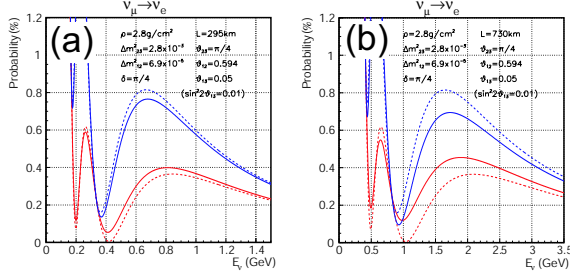


Figure 1. Oscillation probabilities for  $\nu_\mu \rightarrow \nu_e$  (red) and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  (blue) for baseline length of (a) 295 km and (b) 730 km. The solid curves includes asymmetry due to matter effect. For the dashed curves, the matter effect is subtracted and the difference between  $\nu_\mu \rightarrow \nu_e$  (red) and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  (blue) are all due to CP effect.

cillation maximum in 295 km case, the size of the matter effect is much smaller than the CP violation effect, but in the case of 730 km, those sizes becomes comparable. This, in turn, means that, at higher energies, there would be a chance to decide the sign of  $\Delta m^2$  through the matter effect by combining with the lower energy measurements.

### 1.2. Off-axis beam

In many of the future super beam experiments, “off-axis (OA)” beam [12] plays a key role to achieve high sensitivity. In the OA scheme, axis of the beam line components is declined a few degree from the direction to a far detector. In this way, high intensity low energy narrow band beam can be obtained. In order to maximize the sensitivity of the experiments, the peak of the energy spectrum is adjusted close to the oscillation maximum.

## 2. Super-beam experiments

### 2.1. CNGS to Gulf of Taranto (C2GT)

An idea to detect off-axis  $\nu_\mu$  beam from CERN Neutrino Beam to Gran Sasso (CNGS) [13] by a movable underwater Cherenkov detector in the Mediterranean sea (Gulf of Taranto) [9]. The expected spectrum is peaked at  $\sim 800$  MeV, the baseline length can be variable in the range 1,100 $\sim$ 1,700 km and possible fiducial mass could

be 1.5 Mt. The expected number of  $\nu_\mu$  CC interactions without oscillation is estimated to be  $\sim 700$ /year. The purpose of the experiment is the precise measurement of  $\nu_\mu$  disappearance and the search for the  $\nu_e$  appearance. Sensitivity for  $\sin^2 2\theta_{13}$  is about 0.0066 at 90%CL.

### 2.2. Second phase of T2K (T2K-II)

The Tokai-to-Kamioka (T2K) experiment is a next generation LBL experiment in Japan [7]. The  $\nu_\mu$  beam is produced at Japan Proton Accelerator Research Complex (J-PARC) [14] and detected at Kamioka, 295 km apart. The neutrino beam is produced by using a 50-GeV proton synchrotron (PS) in J-PARC.

In the first phase of T2K (T2K-I), the design beam power of the 50-GeV PS is 0.75 MW and the far detector is Super-Kamiokande (SK) of 22.5-kt fiducial mass [10]. The main purpose of T2K-I is discovery of  $\nu_e$  appearance. The T2K-I experiment has been approved in 2003 and the construction of the beam line has been started. The experiment will start in 2009.

Futhurmore, as a future extension of T2K, upgrading the PS to 4 MW and constructing 1-Mt “Hyper-Kamiokande” are also envisaged (T2K-II) [15]. With  $\sim 5$  times higher intensity and about 25 times larger fiducial mass, statistics at SK will be 2 order of magnitude higher than T2K-I. Expected number of  $\nu_\mu$  CC interactions is  $\sim 360,000$ /year with  $2^\circ$  OA beam. The goals of T2K-II are discovery of CP violation and precise measurement of  $\nu_e$  appearance.

Preliminary study on possible upgrade of 50-GeV PS to 4 MW has been made by the J-PARC accelerator group. It is based on (1) increasing repetition rate by doubling number of RF cavities and eliminating idling time in acceleration cycle (factor  $\sim 2.5$ ), (2) doubling number of circulating protons by adopting “barrier bucket” method [16] (factor  $\sim 2$ ).

The expected sensitivity on CP violation in T2K-II based on full detector simulation is plotted in Fig. 2. With the present level of background rejection, the sensitivity is very much depend on the assumption of systematic error. If systematic error of 2% is achieved, then the CP violating phase  $\delta$  can be explored down to  $\sim 20^\circ$

for  $\sin^2 2\theta_{13}$  greater than 0.01.

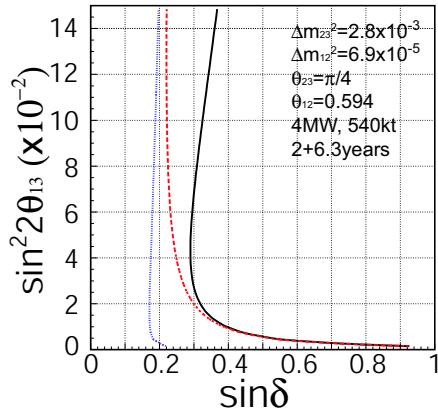


Figure 2. Expected  $3\sigma$  discovery regions of  $\sin \delta$  as a function of  $\sin^2 2\theta_{13}$  after 2 ( $\nu_\mu$ ) and 6.3 ( $\bar{\nu}_\mu$ ) years of exposure in T2K-II. The (blue) dotted curve is the case of no background and only statistical error of signal, (red) dashed one is 2% error for the background subtraction, and (black) solid curve is the case that systematic errors of both background subtraction and signal detection are 2%. The values of other parameters are shown in the plot.

### 2.3. CERN-Frejus project

In Europe, there is an idea of super beam LBL experiment in which the neutrino beam is produced by Super Proton Linac (SPL) and detected by a detector at Modane laboratory in Frejus tunnel, 130 km from CERN [17]. The proposed SPL is a 2.2 GeV linac with 4 MW beam power operated at 75-Hz repetition rate and  $1.5 \times 10^{14}$  protons/pulse. The neutrino beam is a conventional wide-band beam and the expected neutrino spectrum is plotted in Fig. 3. The main component is below 600 MeV and the peak energy is at around 300 MeV. Less NC  $\pi^0$  background is expected for  $\nu_e$  appearance search with this low energy spectrum. The far detector is a UNO type water Cherenkov detector with 440 kton fiducial mass [18]. Expected number of  $\nu_\mu$  CC interactions is  $\sim 15,000/440\text{kt}/\text{year}$  in the case of no oscillation.

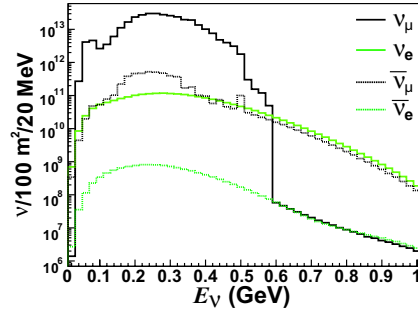


Figure 3. Neutrino spectra for  $\pi^+$  focused beam for a decay tunnel length of 60 m.

Sensitivity on  $\nu_e$  appearance with 5 years of running is  $\theta_{13} = 1.5^\circ$  ( $\sin^2 2\theta_{13} = 0.0027$ ) at 90% C.L. for LMA,  $\delta = 0$ ,  $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{eV}^2$  case as shown in Fig. 4. For sensitivity on CPV,

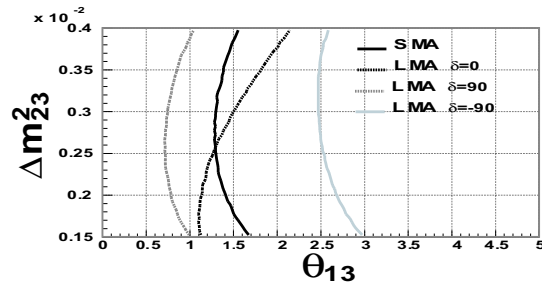


Figure 4.  $\theta_{13}$  sensitivity (90%CL) of CERN-Frejus project. Five years of running is assumed.

2 year run with  $\nu_\mu$  beam and 8 year run with  $\bar{\nu}_\mu$  are assumed. Systematic errors of 2% on both background normalization and signal efficiency are taken into account. No CPV ( $\delta = 0$ ) and  $\delta = 90^\circ$  can be discriminated at 99%CL at  $\Delta m_{12}^2 = 7.3 \times 10^{-5} \text{eV}^2$  if  $\theta_{13} \gtrsim 1.8^\circ$  ( $\sin^2 2\theta_{13} \gtrsim 0.004$ ).

### 2.4. BNL-Homestake project

There is an interest to conduct a (very) long baseline experiment using a neutrino beam from BNL [19]. The neutrino beam is produced by 28 GeV proton beam from AGS at BNL and is detected by a Mton UNO type water Cherenkov de-

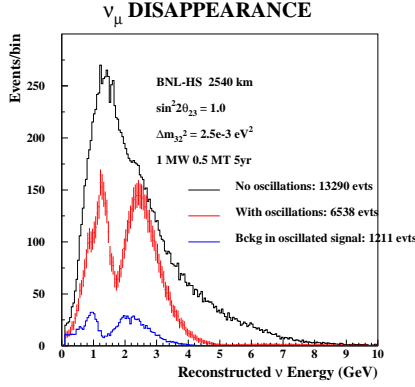


Figure 5. Expected spectrum of detected events in a 0.5 MT detector at 2540 km from BNL including quasi-elastic signal and CC-single pion background with 1.0 MW of beam power in 5 years of running. The top histogram is without oscillations; the middle error bars are with oscillations and the bottom histogram is the contribution of the background to the oscillated signal only. This plot is for  $\Delta m_{32}^2 = 0.0025 \text{ eV}^2$ .

tector in Homestake mine at 2540 km from BNL. The AGS beam power is supposed to be upgraded to 1 MW from present 0.1 MW by introducing 1.2 GeV superconducting LINAC for direct injection and increasing repetition rate [20].

The beam is horn-focused on-axis wide band beam with the spectrum ranging upto about 6 GeV and the peak is at around 2 GeV (Fig. 5). Off-axis option is also a possibility when higher background rejection would become necessary for  $\nu_e$  appearance search. Expected number of  $\nu_\mu$  CC interactions without oscillation is  $\sim 13,000/500\text{kt/year}$ . An alternative detector option of 70-kt liquid Ar TPC [21] is also being studied. Unique feature of this proposal is the large  $L/E$ , where  $L$  is the flight distance and  $E$  is the neutrino energy. Not only the 1st oscillation maximum, but also higher oscillation maxima are covered. The physics goals the project include precise measurement of  $\nu_\mu$  disappearance,  $\nu_e$  appearance search, determination of mass hierarchy, search for CPV. Moreover, thanks to the large  $L/E$ , the solar parameters ( $\theta_{12}$  and  $\Delta m_{12}$ )

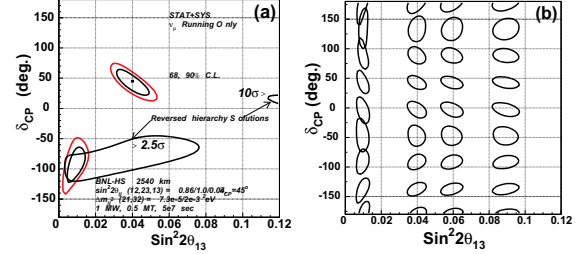


Figure 6. BNL-Homestake sensitivity on (a) mass hierarchy and (b) CP violation for normal hierarchy case.

can be probed.

The expected sensitivities on mass hierarchy and CP violation are drawn in Fig. 6. Only with neutrino running, wrong hierarchy is can be ruled out at more than  $2.5\sigma$ , and by adding anti-neutrino running, the separation becomes more than  $10\sigma$ . The resolution on CP violating phase  $\delta$  is  $20 \sim 30^\circ$  at  $\sin^2 2\theta_{13} = 0.01$  which means that if  $\delta$  is greater than  $20 \sim 30^\circ$ , CPV can be discovered.

## 2.5. Projects at FNAL

At Fermilab, the construction of the MINOS experiment is almost completed and the first beam is planned at the beginning of 2005. The experiment produces  $\nu_\mu$  beam using the 120-GeV 0.4-MW Main Injector (MI) and detects it at Soudan mine, 730km from Fermilab. Recently, an off-axis experiment, NO $\nu$ A, using the same beam as MINOS is proposed [11]. The plan is to construct a new 50-kt fine-grained detector at around 14 mrad off axis and at about 810 km from the production target in Fermilab. The peak position,  $\sim 2 \text{ GeV}$ , of the spectrum is tuned at the oscillation maximum for  $\Delta m^2 \simeq 2.5 \times 10^{-3} \text{ eV}^2$ . The most important goal of the experiment is to discover  $\nu_e$  appearance.

As a possible future extension of the MINOS/NO $\nu$ A experiments, increasing the beam intensity by upgrading the proton driver has been actively discussed. Original idea was to replace the present 8 GeV booster by a new one with larger aperture and doubled repetition rate to achieve 1.9 MW MI power. Recently a new idea to construct a 8-GeV 2-MW superconduct-

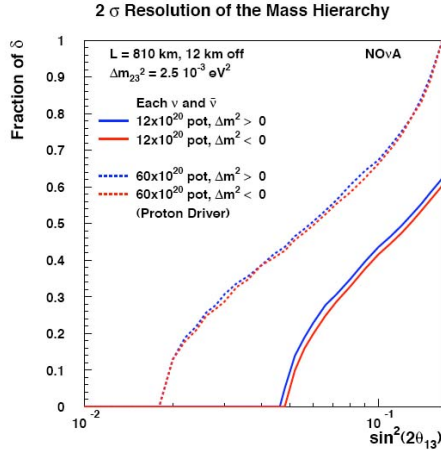


Figure 7. Sensitivity of NO $\nu$ A experiment to mass hierarchy. The solid lines are with the present 0.4 MW beam and the dashed lines are with upgraded 2MW proton driver [11].

ing LINAC and directly inject to MI came into discussion. This option enables flexible operation of MI, because full 2 MW power is available at all energies from 40 to 120 GeV due to negligible injection time compared to the ramping time.

With the upgrade, expected sensitivity of the experiments are improved. As an example, the effect of the upgrade on the sensitivity of the NO $\nu$ A experiment to mass hierarchy is drawn in Fig. 7.

As one of more future possibility with the new proton driver, a case study, FeHo, to send a neutrino beam produced by 120 GeV 2 MW beam and 8 GeV 2 MW beam at the same time to Homestake mine at 1290 km apart from Fermilab [22]. The neutrino energy spectrum ranges up to about 3 GeV with the peak around 1 ~ 2 GeV. With a Mton detector (500 kt fiducial), about 50,000  $\nu_\mu$  CC interactions are expected in one year.

## 2.6. Summary of experiments

Current and future (super beam) LBL experiments are summarized in Table 1. As can be seen in the  $1.27\Delta m^2 L/E$  column, many of the future super beam experiments optimize the neutrino energy spectrum to cover the first oscillation maximum with a off-axis beam. Among

the experiments at the first maximum, T2K is about 3 times closer distance or smaller energy than NO $\nu$ A. Therefore, T2K has less sensitive on matter effect and hence on mass hierarchy while NO $\nu$ A has higher sensitivity on the matter effect. This difference may help to disentangle the oscillation parameters. In that sense, these experiments can play complementary role. The other group of experiments (BNL-Homestake and FeHo) aim to cover higher oscillation maxima as well as the 1st one. The energy dependence of CP violation effect ( $\propto 1/E$ ), matter effect ( $\propto E$ ) are different. The wide coverage of the energy region give a chance to separate these two effects.

## 3. Summary

The next generation “super beam” experiment will provide opportunities to understand the whole view of the neutrino mixing, such as  $\theta_{13}$ , CP violation and mass hierarchy. In the “2nd generation” experiments, sensitivity to the  $\nu_e$  appearance will be improved by more than an order of magnitude from the present upper bound. The CP violating phase  $\delta$  can be probed down to  $\sim 20^\circ$  in the “3rd generation” experiments. Several ideas of super beam experiments have been discussed in US, Europe and Japan. The first 2nd generation experiment T2K in Japan has been approved and started construction in 2004. The experiment start measurement in 2009.

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Table 1: Summary of LBL (super beam) experiments. The first two columns are for proton beam, where  $E_p$  is proton energy. The range of neutrino energy  $E_\nu$  and the detector mass  $M_{\text{det}}$  for future projects are rough round numbers which are read from references. The 6th column,  $1.27\Delta m^2 L/E$  are calculated at  $\Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2$ . Oscillation maxima are expected to be at odd integer for this quantity. The second column from right is the expected number of  $\nu_\mu$  CC interactions.

Experiments	$E_p$ (GeV)	Power (kW)	Beam	$E_\nu$ (GeV)	$L$ (km)	$1.27\Delta m^2 L/E$ ( $\pi/2$ )	$M_{\text{det}}$ (kt)	$\nu_\mu$ CC (/yr)	Status
1st gen									
K2K	12	5	WB	$0.4 \sim 2.5$	250	$0.2 \sim 1.3$	22.5	$\sim 50$	Running
MINOS(LE)	120	400	WB	$1 \sim 6$	730	$0.2 \sim 1.5$	5.4	$\sim 2,500$	Constructing. Start in 2005
CNGS	400	300	WB	$5 \sim 30$	732	$0.0 \sim 0.3$	$\sim 2$	$\sim 5,000$	Constructing. Start in 2006
2nd gen									
T2K-I	50	750	OA	$0.5 \sim 1$	295	$0.6 \sim 1.2$	22.5	$\sim 3,000$	Constructing. Start in 2009
NOvA	120	400	OA	$1.5 \sim 3$	810	$0.5 \sim 1.1$	$\sim 50$	$\sim 4,600$	Proposed.
C2GT	400	300	OA	$0.4 \sim 1$	1,200	$2.4 \sim 6.1$	$\sim 1,500$	$\sim 700$	R&D
3rd gen									
NOvA+PD	120	2,000	OA	$1.5 \sim 3$	810	$0.5 \sim 1.1$	$\sim 50$	$\sim 23,000$	being studied
BNL-Homestake	28	1,000	WB/OA	$0.5 \sim 6$	2,540	$0.9 \sim 10.3$	$\sim 500$	$\sim 13,000$	LOI written
T2K-II	50	4,000	OA	$0.5 \sim 1$	295	$0.6 \sim 1.2$	$\sim 500$	$\sim 360,000$	LOI written
SPL-Frejus	2.2	4,000	WB	$0.1 \sim 0.5$	130	$0.5 \sim 2.6$	$\sim 500$	$\sim 18,000$	being studied
FeHo	8/120	4,000	WB/OA	$0.5 \sim 3$	1,290	$0.9 \sim 5.2$	$\sim 500$	$\sim 50,000$	case study

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